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A comparative evaluation of electric- and gasoline-powered garden tractors

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by

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INTRODUCTION

High energy requirements of agriculture, together with increasing petroleum fuel prices and uncertainty of supply, have led research workers during the last three years to look into alternative possibilities to supplement or substitute for petroleum fuels. Among the alternatives considered are alcohol fuels produced from sugar and starch-rich agricultural products such as sugar cane, corn grain, sorghum, and other crops. Research on ethyl alcohol for fuel use is being conducted in many countries.

Another fuel considered for engine operation is hydrogen produced from water by hydrolysis; however, many technical and economic questions regarding hydrogen fuel are still unanswered.

Some believe that the experience of Western Europe with producer gas generators, fueled with wood chips, corn cobs, or other biomass, shows that these generators can make an important contribution to solving energy problems. In spite of publicity about producer gas generators in Europe, many safety and operational problems are awaiting solution.

Many research workers in the field of energy believe that the use of electricity for vehicle propulsion is a promising solution to petroleum shortages. As reported by Shacket (1979), electric vehicles were in existence from the middle of the 19th century until the beginning of the 20th century. Then the internal combustion engine, with its capabilities of long range, high speed, and suitability for use in rural areas where there was no electricity, as well as in cities, started to replace the motors in electric-powered vehicles. Electric-powered vehicles were out of production by the beginning of the 1930s. However, the previous experience with these vehicles, the past development of the energy-storing devices (batteries), the negligible pollution rate, and low sound levels have renewed the interest in using electric motors to substitute for internal combustion engines, at least in some applications such as for city buses and for light duty farm operations.

The potential advantages of electric-powered vehicles, low operating costs, low pollution, and low noise levels led the U. S. Congress to pass a law entitled "The Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976". The Act is directed towards making advanced technology available at an earlier date, with the primary impact being to provide support to enhance the development of both manufacturing and services industries for electric vehicles. The overall intent of the Act is to shorten the time that would normally be required to introduce a new technology, and to hasten penetration of the market by electric and hybrid vehicles.

Since 1973, a number of patents related to electric-powered tractors (EPT) have been reported, but very few articles were published concerning the actual performance of these tractors. For this research, a series of field experiments were designed to compare the performance of an EPT with that of a similar petroleum-powered tractor (PPT). Since full size electric-powered farm tractors are not made, two garden tractors manufactured by Wheel Horse, South Bend, Indiana, were used. The EPT, Model E-141, and the equivalent PPT, Model C-141, were assigned to similar field jobs. The energy used to perform given tasks and the cost of this energy are important factors in most energy research programs. The energy required and the energy cost are important factors in judging the economy of a tractor in performing a certain task.

Also, it was thought that evaluating the performance of the EPT during winter would give some idea of the type of livestock operations the tractor can handle, since the major farm operations during this season are related to livestock.

Since mowing operations are often done around the farmstead, the sound levels of the two tractors may be a good indicator of the impact of the noise level on the operator and bystanders.

While results of this study are not directly applicable to full size farm tractors, data are presented to compare an electric and a petroleum powered garden tractor when performing a variety of farm tasks.

OBJECTIVES

The overall objective of this study was to evaluate the potential of an EPT as a substitute for a PPT. Specific objectives were:

(1) To study the drawbar performance of the EPT and the PPT.

(2) To compare the energy required to perform a certain field operation with the EPT and the PPT.

(3) To evaluate the energy cost of performing the specific operation with both tractors.

(4) To compare the time required for each tractor to finish the assigned job.

(5) To compare the sound levels at the operator seat when both tractors were operated with and without a mower.

(6) To evaluate the performance of the EPT under different ambient temperatures.

(7) To evaluate the economic feasibility of substituting an EPT for a PPT.

LITERATURE REVIEW

According to Shacket (1979), there were 34,000 electric vehicles registered in the U.S. in 1912. He attributed the disappearance of these early electric vehicles to many factors, such as:

(1) The invention of the electric starter motor in 1911 by Charles F. Kettering, which made the cranking of the gasoline vehicle engine easy. This eliminated a major part of the market for electric vehicles.

(2) The Ford mass-produced Model T gasoline vehicles, originally priced at $850 in 1909, were selling for $260 in 1925. This low price enabled many people to purchase an automobile for the first time.

(3) The electric cars could not appeal to the rural dwellers because of their short range, bad roads, and the unavailability of electricity in rural areas at that time.

(4) The long range and high speed of the gasoline vehicles.
These were the main factors that led to the disappearance of the electric vehicle industry in the early 1930s.

Turrel (1969) tested the Electric Experimental Tractor (EXT) which was introduced by the Farm Electrification Council and Lead Industries Association in 1969. He described the EXT as a four-wheeled riding type tractor, equivalent in capabilities to a twelve horsepower gasoline engine unit. The EXT was powered by six, six volt lead-acid batteries. The tractor had a solid state control which allowed for variation in speed and reversing without loss of power. Two, one horsepower series wound traction motors (2,750 rpm maximum) drove the tractor. Three, 1.25 horsepower permanent magnet motors (4,500 rpm) drove the mower, and one, four horsepower permanent magnet motor drove the snowblower. It also had an electric power lift for attachments.

Turrel reported that his field tests with the EXT showed that the tractor mowed 53,000 square feet in one hour and 15 minutes, using one driver. It also mowed 46,000 square feet in one hour and 25 minutes, using seven different drivers. He found that in snow blowing, the EXT was operated for two hours at a working depth up to nine inches at a speed of 2.4 mph. The tractor cleared snow from 16,800 square feet, and it was backed up a total of one mile during the test. The operator was not able to stall the tractor until he got into a 12-inch drift. Turrel estimated the energy cost for mowing an acre of lawn in 1969 would be 9-12 cents, but he did not give the average cost per kilowatt-hour.

Apple et al. (1971) tested a John Deere Electric 90 riding mower and concluded that battery-powered lawn and garden equipment was feasible. The John Deere Electric 90 riding mower was compared favorably with a seven horsepower gasoline unit, and had sufficient capacity to fulfill the requirements of about 80% of the riding lawn mower market.

Hamlen and Christopher (1971) classified vehicles into six major categories based on gross weight, speed, and range as shown in Table 1. They also discussed the battery power and energy density requirements, shown in Figure 1, and concluded that a 50 to 100% increase in the energy density of the lead-acid battery would greatly increase the

Table 1. Major vehicle categories[a]

Type	Gross weight lbs	Cruise speed mph	Cruise range miles
Off-highway	<2,000	<20	<20
Urban car	2,000	40	50
Commuter car	3,000	60	100
Family car	4,000	70	200
Metro truck	10,000	40	100
Urban bus	20,000	30	125

[a]Hamlen and Christopher (1971).

the number of limited range electric vehicles, and that a sodium-sulfur battery would in the future be useful for general purpose family vehicles and small trucks of range up to 200 miles.

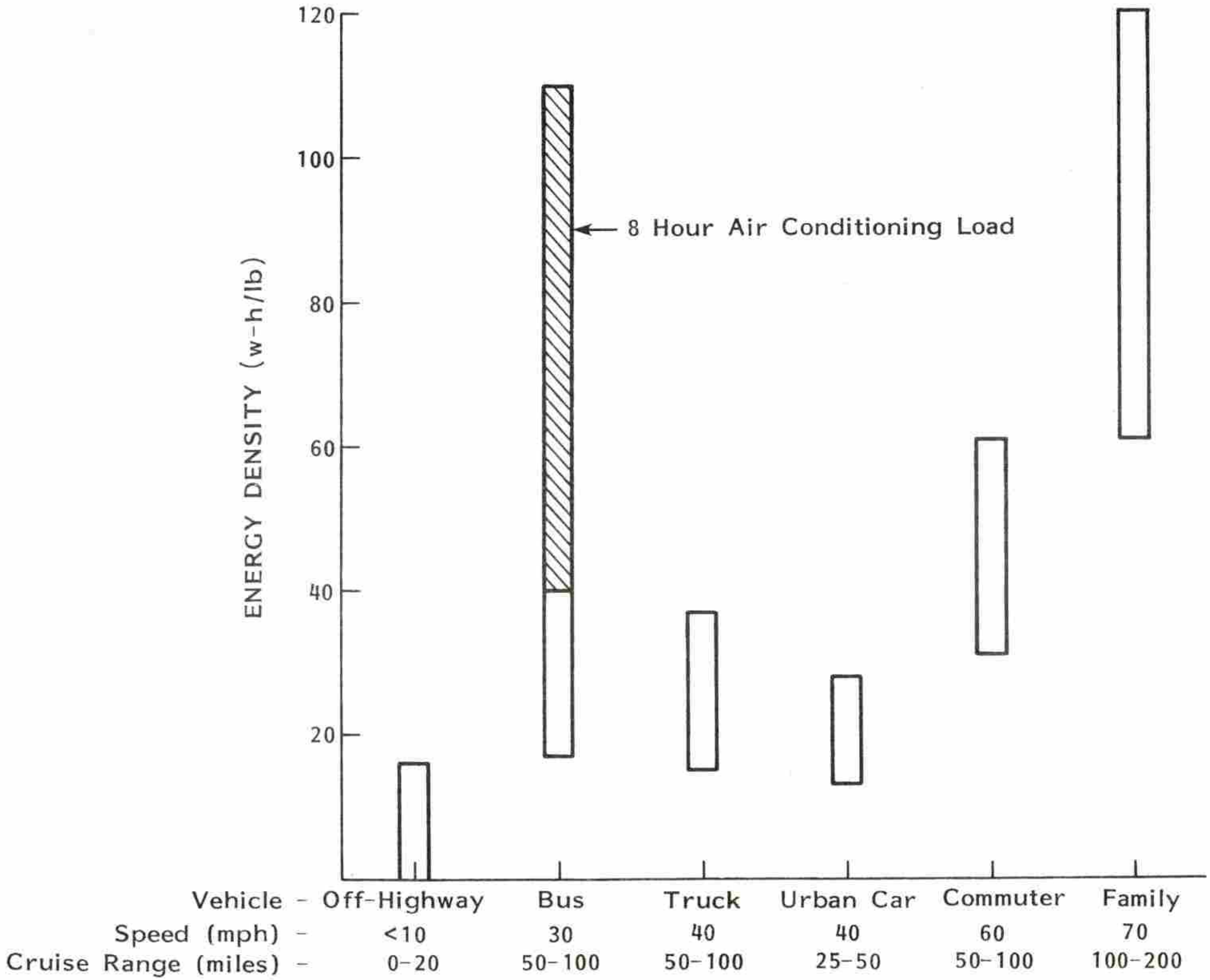
Obert (1972) discussed the feasibility of electric farm vehicles and developed a classification system in terms of duty versus energy density requirements as listed in Table 2.

Table 2. Typical electric vehicles and their duty versus energy density requirement[a]

Application	Duty/charge	Battery watt-hour/lb requirement
Garden tractors	2.0-3.0 acres	12-14
Riding mowers	1.0-2.0 acres	13-15
Walk-behind rotaries	0.5-1.0 hour	14-16
Silage carts	1.0-1.3 hour	12-14
Shredders	1.2-1.5 hour	14-16
Feed carts	1.0-1.3 hour	14-16
Portable power pack	5.0-6.0 hours	12-14

[a]Obert (1972).

Figure 1. Energy density requirements for traction batteries by vehicle (from Hamlen and Christopher (1971))


120
100
80
60
40
20
ENERGY DENSITY (w-h/lb)
8 Hour Air Conditioning Load
Vehicle - Off-Highway Bus Truck Urban Car Commuter Family
Speed (mph) - <10 30 40 40 60 70
Cruise Range (miles) - 0-20 50-100 50-100 25-50 50-100 100-200

Obert also classified battery chargers, based on their designed recharge times, into four basic groups:

(1) High performance chargers--recharge the battery in less than 4 to 6 hours;

(2) Single-shift chargers--recharge the battery in 8 to 10 hours;

(3) Once-a-day chargers--recharge in 12 to 14 hours; and

(4) Infrequent usage chargers--20 to 24 hours recharge time.

He concluded that electric farm vehicles applications were feasible today, and the tools and technical support were available for future feasibility studies and development.

Mauri et al. (1978) compared the future automotive power systems, i.e. an advanced spark ignition engine, a lightweight diesel engine, a battery-powered motor, and a diesel-electric hybrid system. The latter was propelled by an electric motor that received its energy from a diesel engine-driven alternator and an electric battery system. They concluded that the combination of operating costs and energy efficiency would determine which types of advanced power systems offer the best opportunities for development. Their analysis showed that advanced electric-hybrid power systems promised a substantial fuel savings and low operating costs. Their attractiveness was particularly apparent in larger, more powerful cars, where fuel economy advantages could have significant impact on fleet average consumption.

Graumlich and Kern (1974) discussed the typical components of the battery-powered off-highway vehicles. They also studied the performance, size, shape, weight, and the relationship of these components to each other and how they fit together in electric vehicle applications. They mainly looked into golf carts, personnel carriers, riding and walk-behind lawn mowers, two- and three-wheeled bikes, outboard motors, and floor care sweepers and scrubbers. Graumlich and Kern concluded that the hardware and technology were available and were already being applied to many off-highway electric vehicle applications. They also concluded that as new vehicles are planned and developed, electric propulsion systems should be considered as a serious alternative to the internal combustion system.

Turrel (1969), Apple et al. (1971), Hamlen and Christopher (1971), and Graumlich and Kern (1974) all pointed out the advantages of the electric vehicle propulsion systems over the internal combustion system as:

(1) Zero pollutant emissions at the point of use;

(2) Low sound level--nearly all sound emissions came from the drive train and the attachments;

(3) Low operating cost and very low maintenance cost, spread over the long battery life;

(4) Efficiency--electric motors are more efficient than internal combustion engines, offer excellent controllability in speed and direction, and reduce the need for transmissions and differentials;

(5) Instant start;

(6) Safety advantages of low voltage direct current power; and

(7) Portable power source--provides both portable power for remote tool and appliance operation, and is viable standby power source.

Young (1969) discussed the early development of electric vehicles and the reasons for their inability to compete with more economical gasoline driven vehicles. He also compared electric transportation in the U.S. and other countries. He presented some reasons for the growing industrial and commercial transportation market for electric vehicles, in contrast to the slow acceptance of electric passenger vehicles. Young summarized his experience with electric vehicles in the following:

(1) Special purpose vehicles compete well in the commercial, industrial, and farm transportation market.

(2) Present lead-acid batteries are capable of meeting the requirements of a special purpose car of lightweight construction.

(3) Operation costs of electric vehicles are significantly lower than those of comparable gasoline-driven vehicles. He estimated the electric energy cost for a passenger vehicle should be one cent per mile cheaper than that of its gasoline-driven counterpart.

Young (1970) reported that Pacific Gas and Electric Company estimated that 200-300 electric carts were being used on farms of northern California. The carts were used almost exclusively on poultry ranches, where they were used for egg gathering, distributing feed, manure scraping, and removal in cage-type poultry houses. He also reported that Carolina Power and Light Company estimated that a maximum sales potential for electric vehicles on farms in its service area would be one vehicle for every three farms, for a total of 20,000 vehicles. Young discussed the minimum desired characteristics for an electric work vehicle as recommended by the Electric Vehicle Council; these characteristics are listed in Table 3.

Table 3. Desirable characteristics of electric work vehicle[a]

Character	Desired capability
Range	40 miles
Cruising	30 mph
Maximum speed	50-60 mph (for emergency requirement)
Acceleration	30 mph in 10 seconds or less
Seats	Driver and passenger
Pay-load	500 lbs.
Stops per day	150-200 (not required to reach 30 mph after each stop)

[a]Young (1970).

Sheridan et al. (1976) studied the energy utilization of gasoline and battery-powered special purpose vehicles. They concluded that battery-powered vehicles utilize petroleum derived energy much less efficiently than an identically performing spark ignition engine powered vehicle. The use of advanced high energy batteries, increased efficiency electric vehicle components, and significant electric vehicle mass reductions would not reverse the situation. They concluded that it is more efficient to operate petroleum-powered vehicles than to convert the petroleum to electricity and operate electric vehicles. However, they also concluded that it is more efficient to use coal to produce electricity for electric-powered vehicles than to make synthetic gasoline from coal for petroleum-powered vehicles.

DESCRIPTION OF THE TRACTORS[1]

Although direct comparison of performance of an EPT and a PPT of typical farm tractor size was desired, such a comparison was not possible because no EPT that large is being manufactured. The next best choice was to compare two similar commercially produced garden tractors. Two tractors, an EPT and a PPT, manufactured by Wheel Horse were selected. These tractors are of similar size and are intended by their manufacturer to satisfactorily perform similar tasks.

The EPT[2]

Side and front views of the Wheel Horse EPT Model E-141 are shown in Figures 2 and 3, respectively. The tractor mass is 346 kilograms. It is powered by six, 12-volt lead-acid batteries rated at 90 ampere-hours each for a 20-hour discharge cycle. Each fully charged battery is capable of deliverying 25 amperes for 155 minutes. The batteries were manufactured by Prestolite, Toledo, Ohio. The six batteries are series connected into two banks of three batteries, with the banks wired in parallel. Four batteries are located under the tractor hood and two are under the operator's seat. The four front batteries are serviced easily by opening the hood and sliding the tray out; access to the rear two is obtained by tilting the seat, as shown in Figure 4.

The tractor is propelled by a 36-volt, direct current permanent magnet motor shown in Figure 5. The motor has an integral thermal overload

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[1]For specifications on E-141 and C-141, see Appendix B.

[2]E-141 Owner's Manual, Wheel Horse, South Bend, Indiana.

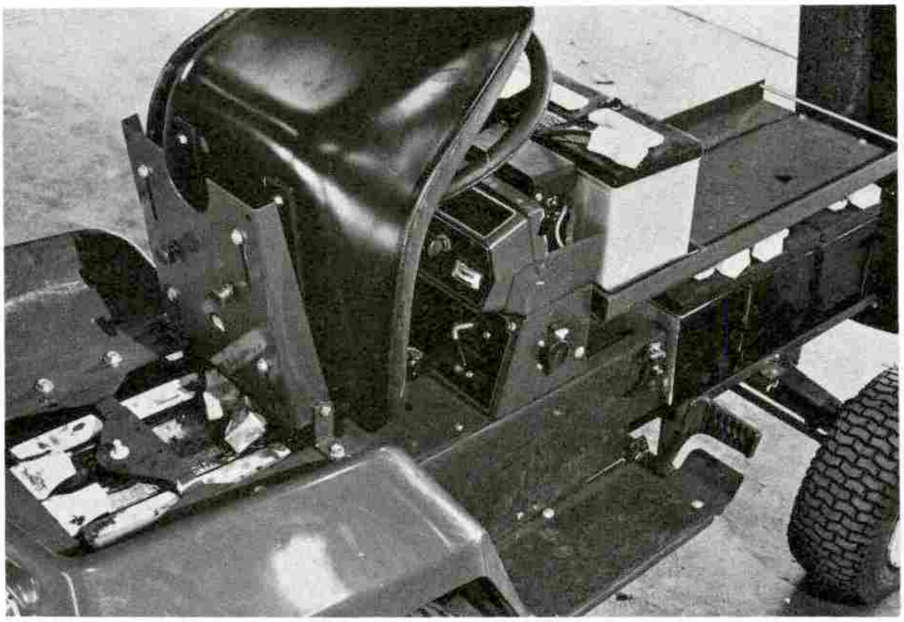
Figure 2. Front view of the EPT, Model E-141

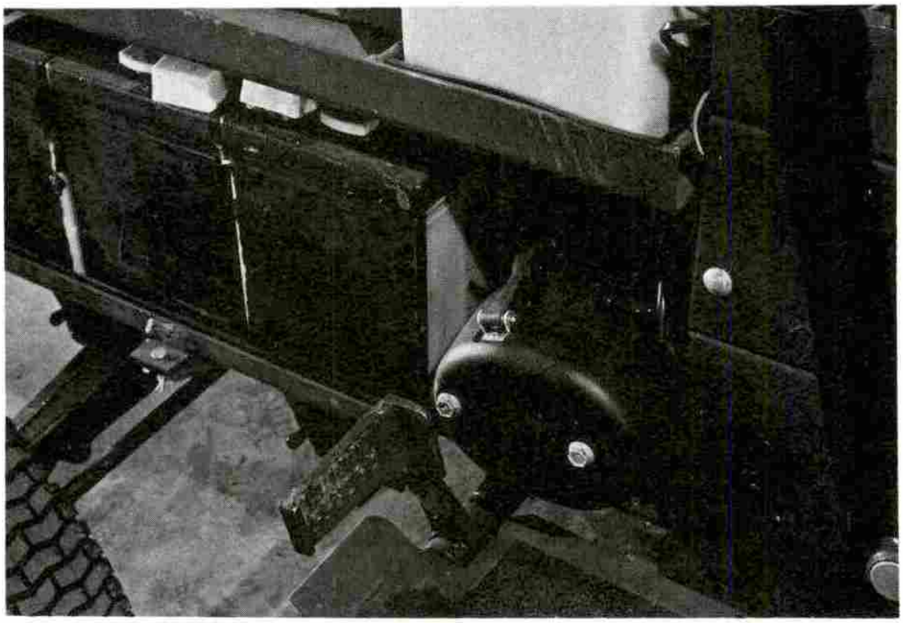
Figure 3. Side view of the EPT, Model E-141


WHEEL HORSE
E-141

Figure 4. Location of the batteries in the EPT (two under the operator's seat and four under the hood)

Figure 5. The driving motor of the EPT





circuit breaker. The motor is rated at 1.25 horse power.[1] No information was available from the owner's manual or from Wheel Horse on the motor speed and weight.

All electrical functions of the tractor, except for the lights, are controlled by the Wheel Horse solid state "brain in a box", shown in Figure 6. The "brain in a box" and the charger work together to recharge the power pack. The "brain in a box" controls the distribution of charging current to the batteries and signals the charger unit to supply various rates of charge current. Also, it controls the even discharge of the batteries, and protects the electrical system, particularly the motor from overloading and overheating by warning the operator with an audio alert system.

The off-board battery charger (8-1570), shown in Figure 7, operates on 120-volt 60 hertz power, and draws approximately 12 amperes. With the aid of the "brain in a box," once the charger is connected, charging is completely automatic. Colored lights are used to indicate the different points in the charging cycle. The red light indicates that charging has begun, the orange indicates approximately 80% recharge, and green indicates a 100% recharge pack. A complete charge cycle will take place in 12 hours or less.

The PPT

The side view of the Wheel Horse PPT Model C-141 is shown, together with the EPT, in Figure 8. The figure shows some differences in height

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[1]The motor rating at 1.25 hp was obtained by telephone from Wheel Horse engineer, Michael C. Freund.

Figure 6. The control box (brain in a box) of the EPT

Figure 7. The charger of the EPT

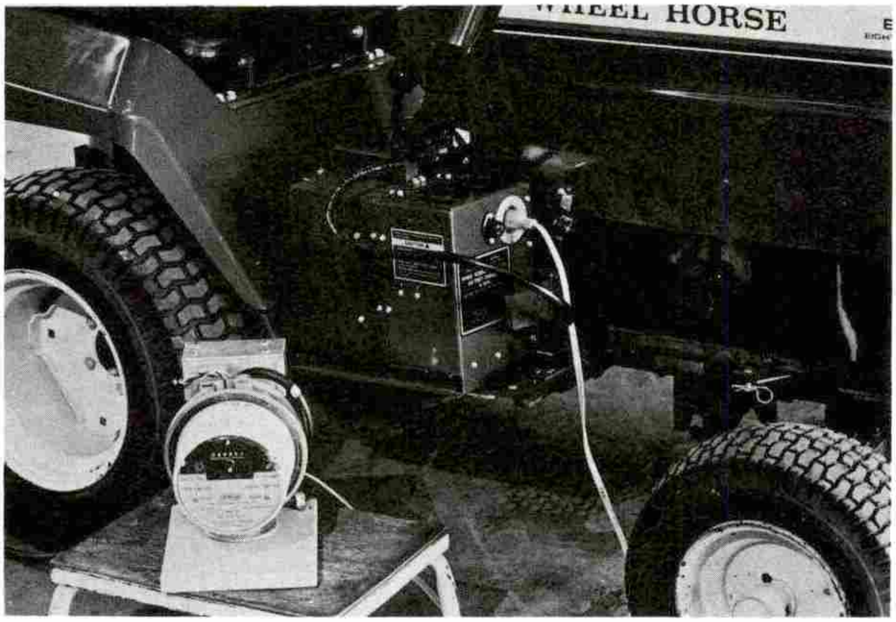
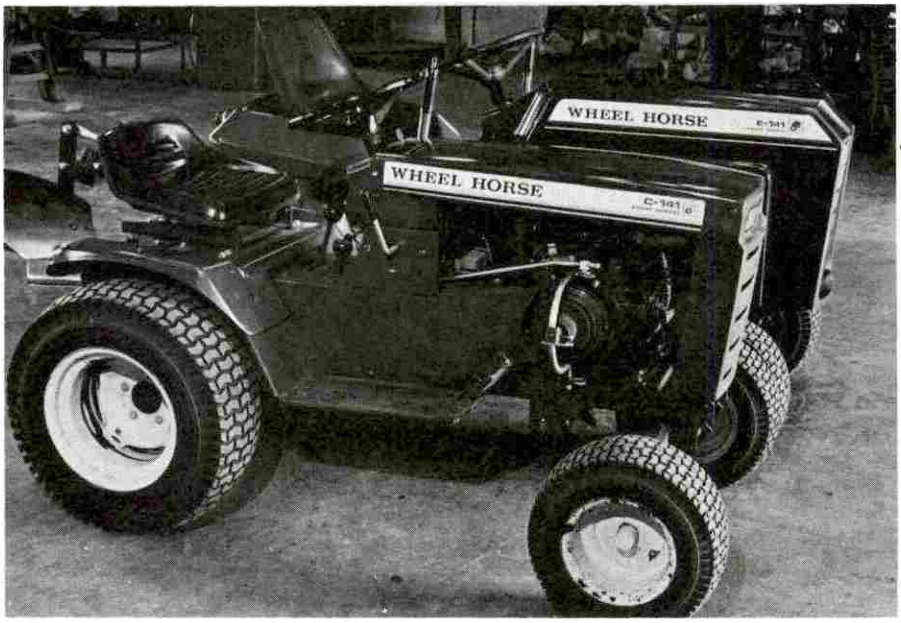

HORSE

Figure 8. The PPT Model C-141 and the EPT Model E-141


WHEEL HORSE
C-141
WHEEL HORSE
C-141

and general size, but both tractors have the same wheel base and length. The tractor is powered by a 16 horsepower Kohler gasoline engine. Mass of the PPT is 277 kilograms. The difference in mass of the two tractors is primarily due to the mass (165 kilograms) of the 6 lead-acid batteries of the EPT.

PROCEDURE

Drawbar Performance

To gain some preliminary information of tractor performance, drawbar power tests of the two tractors were run.

Appendix Tables A1 and A2 were used to record the necessary information on the drawbar power of the EPT and the PPT. Each tractor was run under no load in a specified gear; the distance and the time for 10 drive wheel (rear) revolutions were recorded. Then a dynamometer sled was attached and for the same number of wheel revolutions (10), the distance, the time, and the drawbar pull were recorded. These were measured with a measuring tape, a stopwatch, and a hydraulic load cell, respectively. This procedure was repeated, for both tractors, as the load was increased gradually until the tractor could not move the load or the audio alarm of the EPT gave the overload sound signal.

Field Experiments (Plowing, Disking, and Mowing)

To establish a procedure to collect field data for this study, several preliminary trials were made to determine the most suitable gear (speed) for each operation. The criteria for selecting the gear included the safety of the operator, the quality of the work done, and the safety of the tractor itself. (See EPT description and specification.) The selected gear was used throughout the operation. The engine was operated at full throttle in the case of the PPT. There is no speed control for the motor of the EPT. Field travel speed is controlled by the transmission gear selected and by the drawbar load.

To reduce the errors associated with soil type, moisture content, and human variations, the work was performed with both tractors in the same day, with the same operator, and in randomly assigned plots.

Also, in all experiments the same implement was used with both tractors, except for the mowers. The mower of the EPT is driven by a separate motor, while that of the PPT is driven by a belt and sheave system. However, both mowers are identical in all other respects. The plow (1 x 25 cm) and the disk (107 cm) were used interchangeably with both tractors.

Appendix Tables A3, A4, and A5 were developed to record the necessary field data. The numbers one, two, and three were used to represent plowing, disking, and mowing, respectively. Other headings were used to identify the parameters to be recorded. These are explained as follows:

(1) The time in minutes to cover a certain distance, usually the plot length in meters, while the tractor was in operation, and the total time per plot were recorded from a stopwatch.

(2) The energy used to perform a certain job was measured after operating the tractor, as the energy input needed to bring the tractor to its initial energy status before carrying out the task. So, a 100% charged EPT was towed to the experiment site. The EPT was also towed back to the charging station after the end of the operation. A Duncan watt-hour meter (22-220-514) capable of measuring to the nearest watt-hour was used to measure the energy required to recharge the batteries to the 100% charged condition. Checking the specific gravity of the

electrolyte in each battery before and after charging and maintaining the electrolyte concentration at the level recommended by the manufacturer was done mainly to ensure that the batteries were not a variable in this study; i.e., the energy used in each operation is a function of the operation variables only.

In the case of the PPT, the energy used was measured as the volume of fuel in milliliters required to bring the gasoline level in the tank back to a predetermined level.

(3) The area covered in each operation was measured with a 30 meter measuring tape.

(4) The ambient temperature was measured by a thermometer, to give a general indication of the working temperature.

The Relationship Between Recharging Energy and Time for Stationary EPT Operating with Mower

This test was dictated by certain reasons which are discussed later. Appendix Table A6 was developed to record the energy used when the stationary tractor was operated with the mower for a specified period of time. The watt-hour meter and a stopwatch were used to measure the energy consumed and time, respectively.

Sound Level Measurement

Appendix Table A7 was developed to report the sound levels data for both tractors when working with and without mower. The reason for measuring the sound level with the mower was that the highest sound level was observed in the EPT when working with the mower. The sound level in decibels was measured by a Columbia Model SPL-103 sound level meter at the operator seat, using the A-scale, slow response.

EPT Performance Under Different Temperatures

Appendix Table A8 was developed to record the necessary information on the performance of the EPT under different ambient temperatures. The fully charged EPT was operated with the mower at a certain temperature till the batteries were completely discharged. The total operation time and the temperature were recorded by a stopwatch and a thermometer, respectively. This process was repeated over a temperature range from -4 to 33°C.

STATISTICAL ANALYSIS PROCEDURE

Standard statistical methods were used to analyze and compare various aspects of performance of the EPT and the PPT. The IBM 360 computer at Iowa State University was used to carry out the analyses using the following commands:

```
INPUT JOB$ EPT PPT;
DIFF = EPT - PPT;
CARDS;
    ....    ....    ....
    ....    ....    ....
PROC MEANS t PRT; VAR DIFF;
```

where

INPUT - Description of the arrangement of the variables on the input data lines.

JOB$ - Description of the specific variable to be analyzed.

DIFF - Creation of a new variable, difference, by subtracting the PPT value from the EPT value.

CARDS - Denotes the following cards as the data source.

.... - Represents the data lines.

PROC - Procedure.

MEANS - Arithmetic mean (average).

t - Student's t value for testing a hypothesis.

PRT - Probability (p)[1] of a greater absolute value for the

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[1]*p or **p indicates significance at 5% or 1% level, respectively.

t statistic.

VAR - Variable.

PROC MEANS t PRT; VAR DIFF; these two statements instruct the computer to use the MEANS procedure with the t-test and the p value to test the hypothesis that the value of DIFF is equal to zero.

Graphs

The computer was also used to calculate the intercepts and the slopes for different plots, using the following statement: PROC GLM. This command instructs the computer to use the general linear method (GLM) procedure (PROC) to fit linear equations using the principle of least squares.

RESULTS

Drawbar Performance

These tests were run to provide information on actual drawbar power. They also provide a comparison of actual drawbar power with advertised engine or motor power. The results obtained from the drawbar tests are compiled in Appendix Tables A1 and A2 for the EPT and the PPT, respectively. The equations for calculating the pull (D) in newtons (N), the speed (S) in kilometers per hour (km/hr), and the drawbar power (DBP) in kilowatts (kw) are given by Kepner et al. (1978) as follows:

$$D = \text{Load cell reading, lbs/in}^2 \times \text{piston area, in}^2 \times \frac{4.448\text{N}}{\text{lb}}$$

$$S_1 = \frac{\text{Distance, m}}{\text{time, sec}}$$

$$S = S_1\text{, m/sec} \times \frac{3{,}600 \text{ sec}}{\text{hr}} \times \frac{\text{km}}{1{,}000 \text{ m}}$$

$$DBP = \frac{D\text{, N} \times S_1\text{, m/sec}}{1000\ \frac{\text{N - m}}{\text{sec-kw}}}$$

Hunt (1973) stated that about 0.75 to 0.81 of the net engine power can be transmitted to the drawbar and the rest of the power is lost in gear train friction. However, a maximum of 1.60 kilowatt (Table 4) was recovered at the EPT drawbar at a speed of 3.04 kilometers per hour (second gear high) and a pull of 1890 newtons. At a drawbar load of 2535 newtons the EPT motor was overheated and stopped.[1] On the other

[1]To protect the electrical system of the EPT, the test was stopped at this point.

Table 4. Speed, pull, and drawbar power for the EPT and the PPT

Run no.	EPT (second gear high) Speed (km/hr)	Pull (N)	Power (kw)	PPT (second gear high) Speed (km/hr)	Pull (N)	Power (kw)
1	4.83	0	0	4.94	0	0
2	4.16	778.40	0.90	4.80	444.80	0.59
3	3.97	1112.00	1.23	4.74	1056.40	1.39
4	3.04	1890.40	1.60	4.67	1668.00	2.16
5	2.59	2135.04	1.54	4.58	2201.76	2.80
6	1.95	2535.36	1.39	4.50	2513.12	3.14
7	Motor overheated and smoked			4.40	2613.20	3.19
8				3.71	2969.04	3.06
9				3.07	3135.84	2.67
10				0	2902.32	0

hand, a maximum of 3.19 kilowatts (Table 4) was obtained from the 12 kilowatt engine PPT, at the drawbar at speed of 4.40 kilometers per hour (second gear high) and a pull of 2613 newtons. After the pull of 2613 newtons, adding more weights on the load sled was found to decrease the speed substantially, which overweighed the increase in the pull and hence decreased the drawbar power. At the load of 2902 newtons, the PPT was not able to pull the load any distance (and the engine was stalled).

Field Experiments (Plowing, Disking, and Mowing)

The results obtained from the field tests for plowing, disking, and mowing are shown in Appendix Tables A3, A4, and A5, respectively. To put these results in comparable form, the following procedure was used to calculate the speed in kilometers per hour, the total time required per hectare in hours, the total energy needed per hectare in kilowatt-hours, and the cost per hectare in dollars. (Conversion factors and energy costs are shown in Appendix C.)

The EPT

1. Speed, km/hr $= \frac{\text{Plot length, m}}{\text{Travel time, min}} \times \frac{\text{60 min}}{\text{hr}} \times \frac{\text{km}}{\text{1,000 m}}$

2. Total time required per hectare, hr/ha

$$= \frac{\text{Total time/plot, min}}{\text{Plot area, m}^2} \times \frac{\text{hr}}{\text{60 min}} \times \frac{\text{10,000 m}^2}{\text{ha}}$$

3. Total energy required per hectare, kw-hr/ha

$$= \frac{\text{Energy per plot, kw-hr}}{\text{Plot area, m}^2} \times \frac{\text{10,000 m}^2}{\text{ha}}$$

4. Cost per hectare, \$/ha = Energy required per hectare,

$$\frac{\text{kw-hr}}{\text{ha}} \times \frac{5.98\text{¢}}{\text{kw-hr}} \times \frac{\$}{100\text{¢}} \quad .$$

The PPT

The speed and the total required time per hectare were calculated in the same way as for the EPT; therefore,

1. Total energy required per hectare, kw-hr/ha

$$= \frac{\text{Gasoline used per plot, cm}^3}{\text{Plot area, m}^2} \times \frac{\text{gal}}{\text{3,785.96 cm}^3} \times \frac{1.25 \times 10^5 \text{ Btu}}{\text{gal}}$$

$$\times \frac{\text{kw-hr}}{\text{3,414 Btu}} \times \frac{\text{10,000 m}^2}{\text{ha}}$$

2. Cost per hectare, \$/ha

$$= \frac{\text{Gasoline used per plot, cm}^3}{\text{Plot area, m}^2} \times \frac{\text{gal}}{\text{3,785.96 cm}^3} \times \frac{\$1.00}{\text{gal}} \times \frac{\text{10,000 m}^2}{\text{ha}} \; .$$

The summary of these results, together with t-tests for different operations, is presented in Tables 5a, b and c, 6a, b and c, 7a, b and c, and 11a, b and c for both tractors. In these tables, statistical significance at the 5% level is indicated by a single asterisk and significance at the 1% level is indicated by a double asterisk.

Operating speeds

The same transmission gear was used for the EPT and PPT (second gear, low) for plowing and disking, while second gear high was used for mowing. For all tests, the PPT was operated with the engine speed control lever in the maximum speed position. There is no external speed control of the EPT motor. Motor speed decreases some as load increases. Tables 5a, b, and c compare the operating speeds of the tractors.

Plowing speed for the EPT was significantly lower than for the PPT, although the difference was only 0.12 km/hr. It should be noted that the mean plowing speed of both tractors (1.10 and 1.22 km/hr) is far below the 8 km/hr plowing speed that is typical of full size farm tractors. Also, the disking speed of 1.1 km/hr is even farther below the usual 10 to 11 km/hr farm disking speed.

Operating time per hectare

Tables 6a, b, and c compare the operating times per hectare for the two tractors for three operations. The statistical significance tests are consistent with those for operating speed. Due to the

Table 5a. Comparison of speed in kilometers per hour for plowing

Run no.	EPT speed km/hr	PPT speed km/hr
1	0.97	1.18
2	1.16	1.25
3	1.11	1.21
4	1.12	1.23
5	1.12	1.20
6	1.12	1.24
Mean	1.10**	1.22**

**$p>|t|$ = 0.0016; therefore the hypothesis of equal speeds is rejected.

Table 5b. Comparison of speed in kilometers per hour for disking

Run no.	EPT speed km/hr	PPT speed km/hr
1	1.18	1.13
2	1.18	1.27
3	0.82	0.91
Mean	1.06[a]	1.10[a]

[a]$p>|t|$ = 0.411; therefore the hypothesis of equal speeds is accepted.

Table 5c. Comparison of speed in kilometers per hour for mowing

Run no.	EPT speed km/hr	PPT speed km/hr
1	4.36	4.77
2	4.22	4.57
3	4.06	4.22
Mean	4.21[a]	4.52[a]

[a]$p>|t|$ = 0.0554; therefore the hypothesis of equal speeds is accepted.

combination of small implements and low operating speeds, the time per hectare for each operation is quite high.

Table 6a. Comparison of time required in hours per hectare for plowing

Run no.	EPT time hr/ha	PPT time hr/ha
1	52.04	45.06
2	43.41	43.29
3	46.04	43.62
4	43.34	42.27
5	42.45	41.05
6	44.36	41.26
Mean	45.27*	42.76*

*p>|t| = 0.0517; therefore the hypothesis of equal time is rejected.

Table 6b. Comparison of time required in hours per hectare for disking

Run no.	EPT required time hr/ha	PPT required time hr/ha
1	8.52	9.51
2	8.54	6.51
3	11.61	10.18
Mean	9.56[a]	8.73[a]

[a]p>|t| = 0.4665; therefore the hypothesis of equal time is accepted.

Table 6c. Comparison of time required in hours per hectare for mowing

Run no.	EPT time hr/ha	PPT time hr/ha
1	4.03	3.40
2	4.30	3.85
3	4.62	4.17
Mean	4.32[a]	3.81[a]

[a]$p>|t| = 0.136$; therefore the hypothesis of equal time is accepted.

Energy requirements per hectare

Realistic energy comparisons for the two tractors are difficult, but must be attempted. Tables 7a, b, and c list the measured energy inputs, after converting gasoline consumption of the PPT to equivalent kilowatt-hours. The EPT energy listed is the energy that flowed through the watt-hour meter during battery recharging. As the footnote to these tables suggests, those values should be multiplied by approximately 3 (corresponding to a power plant efficiency of 33%) to obtain the fossil fuel energy equivalent required to generate the electricity. This perhaps puts the electric and petroleum energy delivered to the farm on a roughly equivalent base. Energy is used in pumping oil, and in refining and transporting the finished product. Likewise, energy is used to mine coal (or uranium) and to transport it to the power plant. Electricity distribution losses from the power plant to the farm can be compared to the energy required to transport gasoline from the refinery to the farm.

A major reason for the large decrease in energy from the EPT from Runs 1, 2 and 3 to Runs 4, 5 and 6 (Tables 7a) lies in the fact that for Runs 4, 5 and 6 the batteries were fully discharged before recharging, while for Runs 1, 2 and 3 they were only partially discharged before recharging. This phenomenon is discussed later in this thesis.

Finally, the performance of neither tractor is representative of the energy required for these operations by a full size farm tractor. Hunt (1973) lists typical energy requirements of 14.6 to 25.8 kilowatt-hours per hectare for plowing and 7.4 to 12.9 kw-hrs/ha for disking. Even doubling these values to account for power transmission and traction inefficiencies still leaves a very wide discrepancy between the PPT used and a farm size tractor. Stated another way, the PPT used approximately 76 litres of gasoline to plow one hectare, while Ayres (1976) lists 10 litres (2.7 gallons) as an average value. All of this suggests that garden tractors are not very efficient and are not well suited for performing tillage operations such as plowing and disking.

Table 7a. Comparison of energy required in kilowatt-hour per hectare for plowing

Run no.	EPT energy[a] kw-hr/ha	PPT energy kw-hr/ha
1	193.11	674.70
2	158.66	674.70
3	180.39	779.66
4	88.05	754.22
5	87.30	764.28
6	80.85	755.23
Mean	131.39**	733.80**

[a]Power plant efficiency = 30-38%.

**p>|t| = 0.0001; therefore the hypothesis of equal energy is rejected.

Table 7b. Comparison of energy required in kilowatt-hour per hectare for disking

Run no.	EPT energy[a] kw-hr/ha	PPT energy kw-hr/ha
1	59.02	301.07
2	55.84	243.44
3	61.67	262.65
Mean	58.84**	269.05**

[a]Power plant efficiency = 30-38%.

**$p>|t|$ = 0.006; therefore the hypothesis of equal energy is rejected.

Table 7c. Comparison of the energy required in kilowatt-hour per hectare for mowing

Run no.	EPT energy[a] kw-hr/ha	PPT energy kw-hr/ha
1	84.83	232.27
2	84.29	225.52
3	77.57	222.10
Mean	82.23**	226.63**

[a]Power plant efficiency = 30-38%.

**$p>|t|$ = 0.0002; therefore the hypothesis of equal energy is rejected.

The Relation Between Recharging Energy and Time for Stationary EPT Operating with Mower

The data presented in Appendix Table A6 were plotted as shown in Figure 9. It is very interesting to note that even very short operating times have large energy recharge. The precise reason for this is not understood, but it seems to be a characteristic of lead-acid storage batteries. It was explained by a spokesman for Prestolite

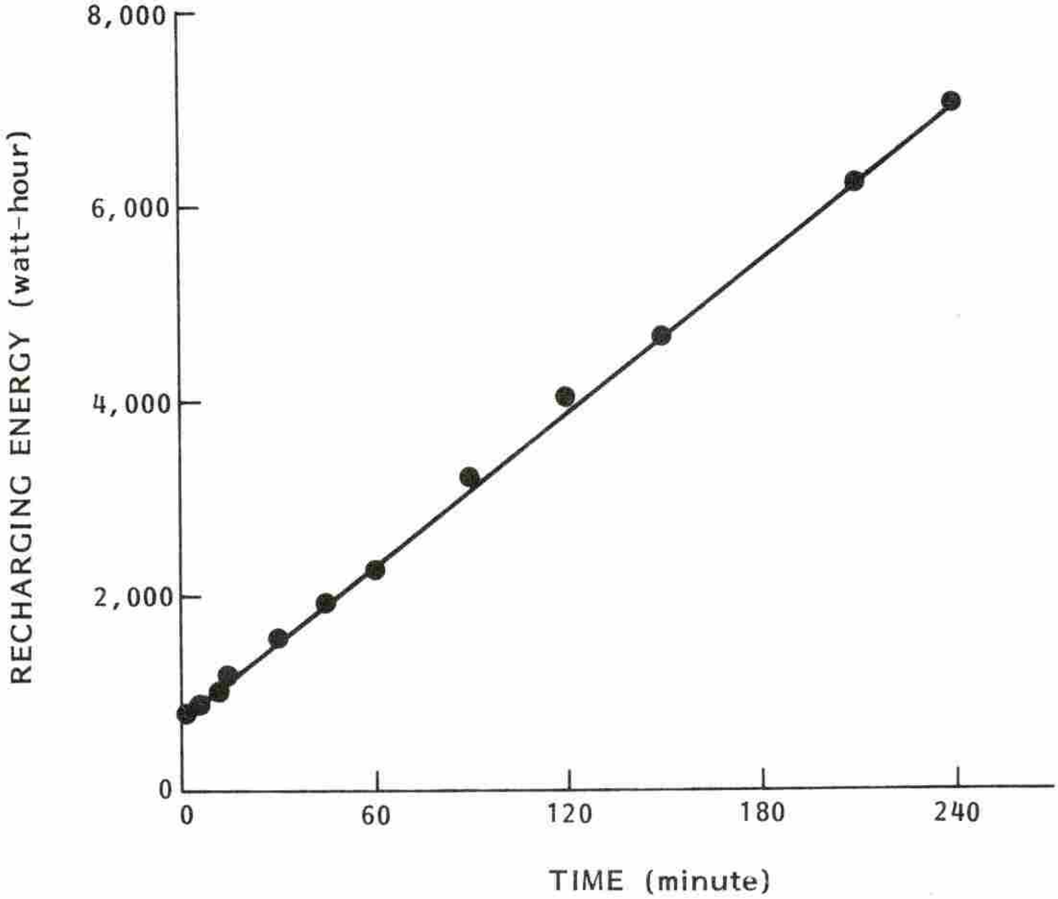

Figure 9. Plot of recharging energy (watt-hour) vs. time (minute) for stationary EPT operating with mower

Company[1], as a surface charge that dissipates very quickly when the fully charged battery is put under load. However, a rapid dissipation of this quantity of energy should result in a substantial heat rise somewhere, which does not appear to occur. More likely the energy is lost during the recharging part of the cycle, that is the charging efficiency (energy stored/energy input) is quite low during the final stages of charging.

Figure 9 also shows an intercept of 733 watt-hour, i.e. about 733 watt-hour will not be possible to recover and use.

Since the machine is charged for the energy input and not the actual energy used, the recharging energy and the cost were recalculated for all field operations performed by the EPT and presented in Table 8 for convenience.

Table 8. Energy and costs per hectare for the EPT[a]

Operation	Data from	Required energy kw-hr/ha	Cost $/ha
Plowing	Tables A3 and 7a	78.71	4.71
Plowing	Tables A3 and 7a	44.27	2.65
Plowing	Tables A3 and 7a	66.00	3.95
Plowing	Tables A3 and 7a	80.36	4.81
Plowing	Tables A3 and 7a	79.62	4.76
Plowing	Tables A3 and 7a	72.48	4.34
Disking	Tables A4 and 7b	7.78	0.47
Disking	Tables A4 and 7b	4.60	0.28
Disking	Tables A4 and 7b	10.43	0.62
Mowing	Tables A5 and 7c	24.79	1.48
Mowing	Tables A5 and 7c	24.25	1.43
Mowing	Tables A5 and 7c	23.86	1.43

[a]Intercept of 733 watt-hrs was deducted before computing energy and costs.

[1]Telephone conversation with Prestolite Company, Toledo, Ohio.

It was also observed that at the end of the recharging cycle, as indicated by the charger green light, the voltage of individual batteries ranged between 13.5 to 14.2 volts, as presented in Table 9. This voltage dropped very quickly to 12.3 volts within the first minute and stayed there for a long time, as shown in Table 10. This may also indicate the quick energy discharge during the initial time of operation.

Table 9. Voltage of individual batteries of the EPT at the end of the recharging cycle

Battery no.	Voltage volts
1	13.85
2	13.78
3	14.02
4	14.20
5	14.00
6	14.01

Table 10. Average voltage of individual batteries at different times for stationary EPT

Time (min)	Voltage volts
0	13.98
1	12.30
25	12.29
28	12.28
34	12.27
40	12.26
45	12.25

Energy Cost Per Hectare

The results in Tables 11a, b and c have been compiled to present the energy cost in dollars per hectare of performing the plowing, the disking, and the mowing operations, respectively. In this study the price of gasoline and electricity used is \$1.00 per gallon and 5.98¢ per kilowatt of electricity, respectively.

Table 11a shows that plowing with PPT costs \$20.05/ha, approximately three times higher than plowing with the EPT (\$7.86/ha). This was almost cut to half for the disking (\$3.52/ha for the EPT and \$7.70 for the PPT), as shown in Table 11b. The difference in cost of mowing with the two tractors is even smaller (\$4.91/ha for the EPT and \$6.49/ha for the PPT), as presented in Table 11c. Also, it is very interesting to observe that disking with the EPT is cheaper than mowing with the same tractor.

Table 11a. Comparison of energy cost in dollars per hectare for plowing[a]

Run no.	EPT cost \$/ha	PPT cost \$/ha
1	11.55	18.43
2	9.49	18.43
3	10.79	21.30
4	5.27	20.60
5	5.22	20.88
6	4.83	20.63
Mean	7.86**	20.05**

[a]Electricity @ 5.98¢/kw-hr; gasoline @ \$1.00/3.876 litre.

**$p<|t|$ = 0.0006; therefore the hypothesis of equal costs is rejected.

Table 11b. Comparison of energy cost in dollars per hectare for disking[a]

Run no.	EPT cost \$/ha	PPT cost \$/ha
1	3.53	8.62
2	3.34	6.97
3	3.69	7.52
Mean	3.52**	7.70**

[a]Electricity @ 5.98¢/kw-hr; gasoline @ \$1.00/3.876 litre.

**$p>|t|$ = 0.0144; therefore the hypothesis of equal costs is rejected.

Table 11c. Comparison of energy cost in dollars per hectare for mowing[a]

Run no.	EPT cost \$/ha	PPT cost \$/ha
1	5.07	6.67
2	5.04	6.45
3	4.63	6.36
Mean	4.91**	6.49**

[a]Electricity @ 5.98¢/kw-hr; gasoline @ \$1.00/3.876 litre.

**$p>|t|$ = 0.0034; therefore the hypothesis of equal costs is rejected.

Sound Level

The summarized results of the sound level measurements from Appendix Table A7 together with the t-test are presented in Tables 12 and 13. The average sound level of both tractors (92.7 dBA for the EPT and 96.3 for the PPT) is above the safe limit of 90 dBA for 40 hours of exposure per week when operated with the mower, as shown in Table 11. However, this continued to hold for the PPT when operated without the mower (92.2 dBA) and dropped to an average of 71.0 dBA for the EPT.

Table 12. Comparison of sound levels for both tractors with mower

Run no.	EPT sound level dB(A)	PPT sound level dB(A)
1	92.6	96.0
2	93.0	96.0
3	93.0	97.0
4	92.5	96.0
5	92.6	96.5
Mean	92.7**	96.3*

**p>|t| = 0.0001; therefore the hypothesis of equal sound levels is rejected.

Table 13. Comparison of the sound levels for both tractors without mower

Run no.	EPT sound level dB(A)	PPT sound level dB(A)
1	72.0	91.0
2	70.0	92.0
3	71.0	93.0
4	71.5	92.5
5	70.5	92.5
Mean	71.0**	92.2**

**p>|t| = 0.0001; therefore the hypothesis of equal sound levels is rejected.

EPT Performance Under Different Temperatures

The data from Appendix Table A8 were plotted, as shown in Figure 10. The figure shows an intercept of 4.51 hours and a slope of 0.04 hour/°C.

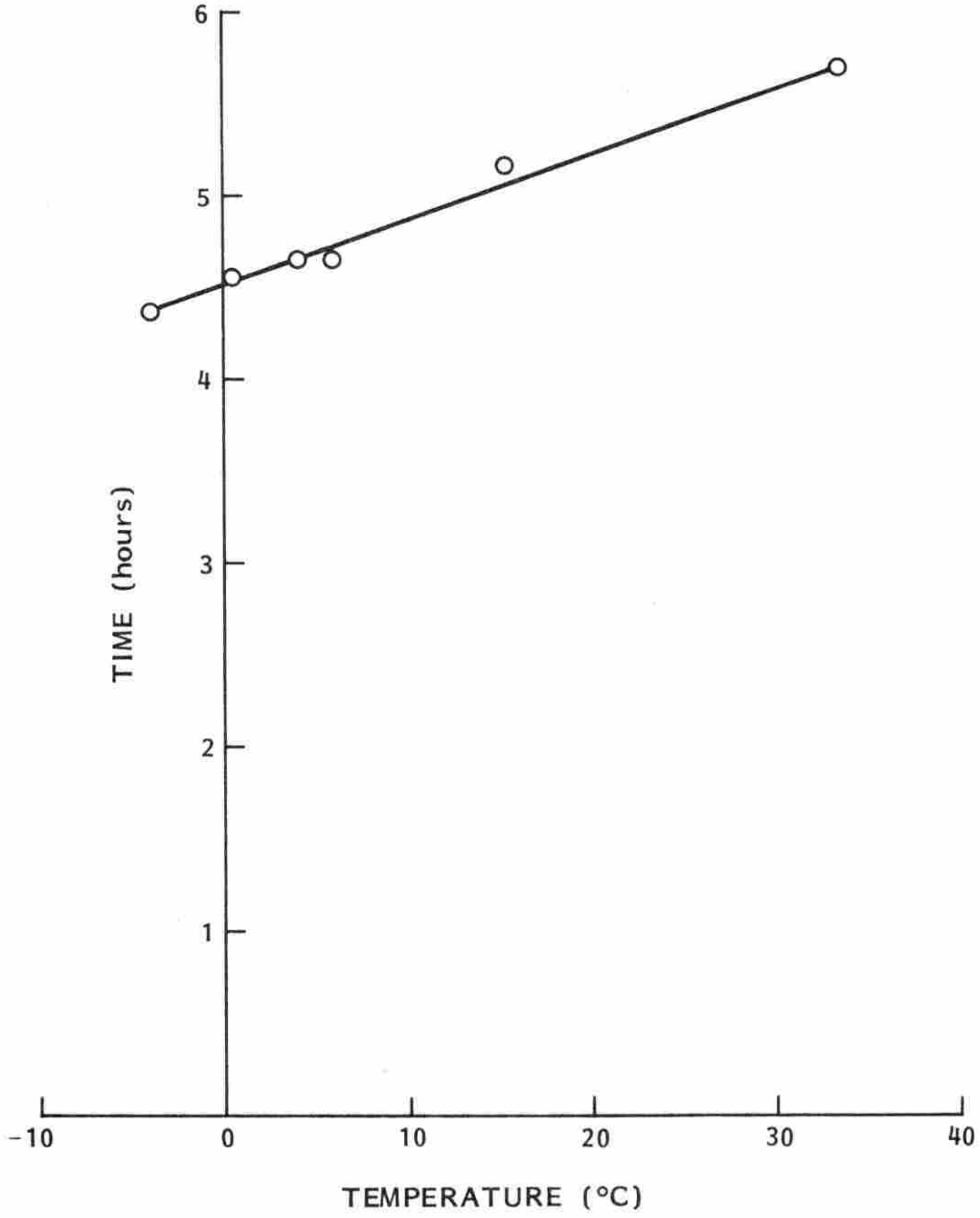

Figure 10. Plot of time of operation in hours vs. ambient temperature in degrees Celsius for stationary EPT operating with mower

DISCUSSION

Field Experiments

Total time per hectare and speed

Since the speed is a function of time, it will be instructive to discuss the speed and the total time per hectare as one group. The results of the speed and the total time per hectare tests together with the t-test were presented in Tables 4a, b, and c and Tables 5a, b, and c respectively. The t-test shows that there is no significant difference for the two tractors in total time per hectare and speed for disking and mowing but a highly significant difference in speed for plowing. However, even though statistically significant, the speed difference is only 0.12 km/hr.

The rated ground speeds for both tractors at different gears are generally the same (see Appendix B, Tractors Specifications). Since both tractors were operated with the same implements and at the same gear, the result that there is no significant difference in total time per hectare and speed is expected.

The combined effect of weight (EPT weight = 3567 newtons and the PPT weight = 2646 newtons) and plowing depth may lead to the differences in time and speed for the plowing operation. It was observed that for the same plow adjustment, the plowing depth with the EPT (6-8 inches) is relatively deeper than the plowing depth when working with the PPT (3-5 inches). Effort to adjust the plow to go to a relatively equal depth for both tractors yielded a very shallow plowing (2-3 inches);

and for deep plowing, the PPT was not stable and tended to tip backwards. The EPT plowing depth was 1-3 inches deeper than PPT for any plow adjustment deeper than 4 inches. Unlike the PPT, the EPT plowing depth was stable for any depth. As the depth increased, there was a significant reduction in the speed due to the high draft and wheel slip. From this it is evident that the weight of the EPT has led to the deep plowing which significantly increased the total required time per hectare and reduced the speed of the EPT below that of the PPT. However, the time per hectare for plowing with the EPT was only 6% greater than for the PPT.

Total required energy per hectare

Tables 6a, b, and c have been compiled to present the energy consumption of both tractors in kilowatt-hours for different field operations. The t-tests show a highly significant difference for energy consumption by both tractors for all field operations. This substantial energy difference may be due mainly to the efficiency of energy conversion by both systems. Liljedahl et al. (1979) stated that internal combustion engines are relatively inefficient energy converters; their efficiencies range between 25 and 35%. Also Sargent et al. (1978) stated that the direct current motors designed for use in industrial trucks can have an efficiency of up to 80% at 36 volts and 75 amperes, falling off to 62% at 575 amperes. These two statements by Liljedahl and Sargent agree reasonably well and support the highly significant differences in energy consumption by the EPT and the PPT for all the operations investigated in this study. One reason for the attractiveness of electricity as a power source is that it can be produced from renewable sources such as biomass and hydropower. Sheridan et al. (1976) found that the efficiency of most electric power plants in the United States ranges between 32-38%. This is not a great deal higher than the 25 to 35% efficiency that Liljedahl et al. (1979) quote for internal combustion engines, but the electricity can be generated from coal, which is abundant in the United States.

Table 6a shows a large difference between the required energy per hectare values for the EPT for different test runs. The first three observations were calculated from 17 to 22 minutes of plowing, while the last three observations were calculated from 4.28 to 4.44 hours of operation.

Since the whole electrical system, including the batteries, of the EPT was checked periodically and preserved in good condition, the data in Appendix Table A4 were plotted as presented in Figure 9. The figure shows an intercept of 733 watt-hours which means that that much energy input will not be possible to recover and use.

It was also observed that at the end of the recharging cycle, as indicated by the charger green light, the voltage of individual batteries ranged from 13.5 to 14.2 volts as presented in Table 9. This voltage dropped down very quickly within the first 40 seconds of operation to 12 volts and stayed there for two to four hours. Evidently, this voltage drop occurs with little dissipation of energy, but recharging to the 14 volt level is an inefficient process.

This phenomenon, as stated by Prestolite Company,[1] is characteristic of all lead-acid batteries. There is unrecoverable surface charge which dissipates very quickly during the first minute of closing the electric circuit.

Since the machine is charged for the energy input and not the actual energy used, the recharging energy and the cost were recalculated for all field operations performed by the EPT and presented in Tables 7a, b, and c for convenience.

Economic Analysis

Major factors affecting whether a machine or system will be adopted in agriculture are the economy of the system and its ability to perform the job under consideration in a timely manner. The tractors used in this study are not timely for field operations because of their small size. However, they permit some comparative evaluation when performing field operations. Any economic advantages of the electric system will enhance the probability of the construction of a large size EPT capable of handling field operations such as disking and plowing.

To make a complete economic comparison, certain assumptions must be made. These assumptions are:

(1) For the EPT to be available 12 hours per day to perform any operation, three battery packs are required. Each pack costs \$300 (6 batteries/pack x \$50/battery).

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[1]Telephone conversation with Prestolite Company, Toledo, Ohio.

(2) The economic life, (n), of the EPT is 10 years (based on three battery packs) and also 10 years for the PPT (suggested by Kepner et al., 1978).

(3) Depreciation (D_e for the EPT and D_p for the PPT) is calculated by using the straight line method:

$$D = \frac{B - V}{n} \qquad \text{(Kepner et al., 1978)}$$

where D = depreciation, loss in value with passage of time, dollars per year,

B = first cost of the tractor, dollars,

V = salvage value of the tractor, dollars, and

n = economic life, years.

(4) V for each tractor is 10% of B.

(5) Interest rate (I) is 15% of (B + V)/2 (Kepner et al., 1978).

(6) Taxes, insurance, and shelter, 2% of B.

(7) Lubricant cost, 15% of fuel or electricity cost per hour.

(8) The average repair cost per hour, 0.01% of B.

(9) Labor, $4.5 per hour.

(10) Total hours of use, 500 hours per year (in Iowa, farm tractors are used 400 to 600 hours per year).

$$B_e = \$2352$$

$$B_p = \$2085$$

where B_e and B_p are the B for the EPT and the PPT, respectively.

EPT

Annual fixed charges

$$D_e = [2352 - (0.10)(2352)]/10 \qquad = \$211.68$$

$$I = 0.15[2352 + (0.10)(2352)]/2 \qquad = 194.04$$

$$\text{Taxes, insurance, and shelter} = 0.02 \times 2352 \qquad = \underline{\ 47.04\ }$$

$$\text{Total fixed cost per year} \qquad \$452.76$$

Cost per hour

$$\text{Fixed cost} = \$452.76/\text{year} \times \frac{1}{500\ \text{hr/year}} \qquad = \$\ 0.91$$

Electricity @ 5.98¢ per kilowatt-hour =

$$[8.588\ \text{kw-hr/charge} \times \frac{1}{4\ \text{hr/charge}}]^{1} \times \frac{5.98¢}{\text{kw-hr}} \times \frac{\$}{100¢}$$

$$= 0.13$$

$$\text{Repair} = \frac{0.01}{100}(2352) \qquad = 0.24$$

Lubricant (15% of electricity cost) =

$$0.15(0.13) \qquad = 0.02$$

$$\text{Labor} \qquad = \underline{\ 4.50\ }$$

$$\text{Total cost per hour} \qquad \underline{\underline{\$5.80}}$$

PPT

Annual fixed charges

$$D_p = [2085 - (0.10)(2585)]/10 \qquad = \$187.65$$

$$I = 0.15[2085 + (0.10)(2085)]/2 \qquad = 172.01$$

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[1] See Appendix Table A3; 8.588 kw-hr is the average for the last three replicates when a full charge was used.

Taxes, insurance, and shelter = 0.02(2085)	=	\$ 41.70
Total fixed cost per year	=	\$401.36

Cost per hour

Fixed cost = $\$401.36/\text{year} \times \frac{1}{500\ \text{hr/year}}$	=	0.80
Repair = $\frac{0.01}{100}$ (2085)	=	0.21
Fuel @ 26.4¢ per litre[1] = 1.84 litre/hr[2] x 26.4¢/litre	=	0.49
Lubricant (15% of fuel cost) = 0.15 x 0.49	=	0.07
Labor	=	4.50
Total cost per hour		\$6.07

These calculations, as the footnotes suggest, are based on a full discharge of the EPT during plowing, and the equivalent of this in the case of the PPT (run numbers 4, 5, and 6 in Appendix Table A3). Since both tractors used the same plow, including it in the calculation will not make any difference.

The per hour costs for both tractors, based on 500 hours per year, are very small (\$5.80/hr for the EPT and \$6.07/hr for the PPT) and can lead to inaccurate conclusions. On the other hand, the per year costs for each tractor are even more than the price of the tractor itself.

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[1]One gallon of gasoline costs one dollar, and one gallon = 3.785 litres.

[2]See Appendix Table A3; 1.8¢ litre per hour is the average equivalent to full charge of the EPT.

$$\text{Total costs per year for the EPT} = \$5.80/\text{hr} \times \frac{500\ \text{hr}}{\text{year}} =$$

$$\$2{,}900\ (\text{B of EPT is } \$2352)\ .$$

$$\text{Total costs per year for the PPT} = \$6.07/\text{hr} \times \frac{500\ \text{hr}}{\text{year}} =$$

$$\$3035\ (\text{B of PPT is } \$2085).$$

Comparing the two tractors on a per hour basis showed that the hourly cost of the EPT was 5% (27 cents per hour) less than the PPT when the two extra power packs are considered. If the per hour cost is recalculated based on one battery pack, usually included within the original price of the EPT, the per hour cost difference between the EPT and the PPT will be 9% (53 cents per hour).

If the labor cost was not considered, the electricity cost for the EPT would be only 10% (13 cents per hour) of the total cost ($1.30 per hour), and the gasoline cost for the PPT would be 31% (49 cents per hour) of the total cost ($1.57 per hour).

Since the timeliness factor was eliminated from this comparison, as mentioned previously, it will be interesting to note that the per hectare costs for the EPT and PPT are $262.57 and $259.55, respectively.

Sound Level

It is generally recognized that exposure of 40 hours per week to a sound level of 90 dBA or greater will produce permanent hearing loss. This process of hearing loss usually occurs slowly and painlessly.

It is evident that both tractors exceed the 90 dBA when operated with mower as presented in Table 12. The sound level of the EPT is significantly less than that of the PPT but still within the unsafe limit.

SUMMARY AND CONCLUSIONS

The major objective of this study was to compare the performance of an EPT with performance of a PPT. Since full size electric powered farm tractors are not produced, two garden tractors were used.

The scope of this study included three major field operations, which the EPT and the PPT can carry out without modifications or implement adaptation; i.e., both tractors were mainly tested on jobs for which they were designed. Speed, time, energy consumption, cost, and sound level were the major variables in this research. Other experiments were conducted either to find an explanation for inconsistent observations (required energy per hectare for plowing with the EPT), or to investigate the capabilities of the EPT in different operating conditions (performance of the EPT under different temperatures).

The results of this study lead to the following conclusions.

(1) There are no significant differences between the EPT and the PPT with respect to the total required time per hectare and tractor operating speed for all operations except plowing. The combined effect of the greater EPT weight and plowing depth resulted in slower speed and increased field time for the EPT.

(2) There were substantial energy savings for the EPT for all field operations. This is because the direct current electric motors are more efficient energy converters than small internal combustion engines. In making the energy comparisons, an overall power plant and electricity transmission efficiency of 30-38% was used.

(3) The lead-acid batteries when charged with the charger used in this study can be overcharged (1.5 to 2.2 volts higher). This extra surface charge dissipates very quickly in tractor operation and contributes little useful energy.

(4) The EPT was more economical to operate in terms of energy cost than the PPT for all the considered operations. Energy costs for this comparison were 5.98¢/kw-hr for electricity and $1.00/gallon of gasoline.

(5) Noise levels from both tractors exceeded 90 dB (maximum permissible 8-hr noise level) when working with the mower. However, this result continued to hold for the PPT when operated without the mower, while this was not the case for the EPT.

(6) There is a linear positive relationship between operating time on a full battery charge and ambient temperature for the EPT. The line has an intercept of 4.51 hours and a slope of 0.04 hour/°C. This equation can be written as

$$t = 4.51 + 0.04T$$

where

t = total operating time on a full charge, hours, and

T = temperature, °C.

The temperature range tested was from -4 to 33°C.

(7) Fuel costs are a fairly small part of the total cost of operation (even if you leave labor out), and the total cost for the two tractors probably isn't much different. However, the EPT could still be a good choice based upon fuel availability and the ability to

substitute energy from coal (electricity) for petroleum.

Suggestions for Further Research

The general form of this research provides a practical and realistic procedure for comparative evaluation of electric powered and petroleum powered tractors, based on actual field tests. It furnishes a data base in this field for further investigation. However, performance of these small tractors is not necessarily representative of performance of "full-size" agricultural tractors.

Further research might include:

(1) A study of the most desirable type of storage battery for tractor power.

(2) A study of some existing larger electric powered vehicles, such as fork-lift trucks and earthmoving equipment with electric traction motors.

(3) A study of the transmission design changes that might be appropriate for an EPT, since the torque-speed characteristics of electric motors and internal combustion engines are quite different.

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APPENDIX A: FIELD AND LABORATORY DATA

Table A1. Drawbar test for the EPT

Run no.	Gear	Dynamometer		Distance for 10 drive wheel revolutions (ft)	Time (sec)	Remarks
		Pressure (psi)	Pull (lb)			
1	Second high	0	0	59.29	13.4	
2	Second high	70	175	58.67	15.4	
3	Second high	100	250	58.29	16.0	
4	Second high	170	425	57.83	20.8	
5	Second high	192	480	57.39	24.2	
6	Second high	228	570	56.96	31.8	Motor smoked and stopped

Table A2. Drawbar test for the PPT

Run no.	Gear	Dynamometer		Distance for 10 drive wheel revolutions (ft)	Time (sec)	Remarks
		Pressure (psi)	Pull (lb)			
1	Second high	0	0	58.0	12.8	
2	Second high	40	100.0	57.13	13.0	
3	Second high	95	237.50	56.39	13.0	
4	Second high	150	375.00	55.63	13.0	
5	Second high	198	495.00	55.29	13.2	
6	Second high	226	565.00	54.42	13.2	
7	Second high	235	587.50	53.21	13.2	
8	Second high	267	667.50	45.33	13.3	
9	Second high	282	705.00	37.50	13.3	
10	Second high	261	652.50	0	13.3	

Table A3. Plowing

Rep. no.	Temperature (°C)	Plot length (m)	Plot area (m^2)	EPT (second gear low)			PPT (second gear low with full throttle opening)		
				Average traveling time/plot length (min)	Total time/plot (min)	Energy used/plot (watt-hr)	Average traveling time/plot length (min)	Total time/plot (min)	Energy used/plot (ml)
1[a]	19	23	67.63	1.42	21.12	1306	1.17	18.28	4352
2[b]	17	23	67.63	1.19	17.62	1073	1.10	18.57	4352
3[c]	19	23	67.63	1.24	18.68	1220	1.14	19.70	5029
4[d]	3	50	1008.52	2.68	262.10	8878	2.44	255.60	7500
5[e]	4	50	1008.52	2.67	256.83	8803	2.51	240.60	7600
6[f]	3	50	999.98	2.68	266.15	8083	2.42	241.80	7510

[a] 6 November 1980.
[b] 7 November 1980.
[c] 8 November 1980.
[d] 28 November 1980.
[e] 29 November 1980.
[f] 30 November 1980.

Table A4. Disking

Rep. no.	Temperature (°C)	Plot length (m)	Plot area (m^2)	EPT (second gear low)			PPT (second gear low with full throttle opening)		
				Average traveling time/plot length (min)	Total time/plot (min)	Energy used/plot (watt-hr)	Average traveling time/plot length (min)	Total time/plot (min)	Energy used/plot (ml)
1[a]	13	23	151	1.17	7.72	891	1.22	8.62	470
2[b]	6	23	151	1.17	7.73	843	1.09	5.90	380
3[c]	13	23	151	1.68	10.52	931	1.52	9.22	410

[a]10 November 1980.
[b]11 November 1980.
[c]12 November 1980.

Table A5. Mowing

Rep. no.	Temperature (°C)	Plot length (m)	Plot area (m^2)	EPT (second gear high)			PPT (second gear high with full throttle opening)		
				Average traveling time/plot length (min)	Total time/plot (min)	Energy used/plot (watt-hr)	Average traveling time/plot length (min)	Total time/plot (min)	Energy used/plot (ml)
1[a]	13	30.5	128.84	0.42	3.12	1093	0.38	2.63	310
2[b]	4	30.5	128.84	0.43	3.33	1086	0.33	2.98	300
3[c]	8	30.5	139.35	0.45	3.86	1081	0.43	3.48	320

[a]31 October 1980.
[b]2 November 1980.
[c]3 November 1980.

Table A6. Relationship between recharging energy and time for stationary EPT operating with mower

Run no.	Time min.	Recharging energy watt-hr	Run no.	Time min.	Recharging energy watt-hr
1	1	826	7	60	2286
2	6	870	8	90	3230
3	12	1002	9	120	4020
4	15	1197	10	150	4656
5	30	1573	11	210	6232
6	45	1948	12	240	7033

Table A7. Sound level at the operator's seat

Run no.	EPT		PPT	
	Sound level[a] dB(A)[c]	Sound level[b] dB(A)[c]	Sound level[a] dB(A)[c]	Sound level[b] dB(A)[c]
1	92.6	72.0	96.0	91.0
2	93.0	70.0	96.0	92.0
3	93.0	71.0	97.0	93.0
4	92.5	71.5	96.0	92.5
5	92.6	70.5	96.5	92.5

[a]With mower.
[b]Without mower.
[c]Sound level meter using A-scale, slow response.

Table A8. Relationship between time of operation in hours and temperature in degrees Celsius for stationary EPT operating with mower

Run no.	Time of operation (hr)	Temperature (°C)
1	4.35	-3.90
2	4.55	0.56
3	4.67	4.00
4	4.68	6.00
5	5.70	33.50
6	5.17	15.51

APPENDIX B: TRACTORS SPECIFICATIONS

PPT (C-141) Specifications[1]

Engine:

Model	:	Kohler 321AS
Horsepower rating	:	14
Displacement	:	512.4 CC
Bore	:	88.9 mm
Stroke	:	82.6 mm
Ignition	:	Battery

Transmission:

Type	:	Mechanical, all gear
Number of forward speeds	:	6
Number of reverse speeds	:	2

Approximate ground speeds at full throttle :

Gear	Low range	High range
First	0.8 km/hr	3.2 km/hr
Second	1.3 km/hr	5.2 km/hr
Third	2.2 km/hr	8.8 km/hr
Reverse	1.0 km/hr	4.2 km/hr

Electrical system: The electric motor is connected through a clutch to the transmission. There is no electrical speed control for the motor.

Type:	12 volt d-c, negative ground
Alternator:	12 volt, 3 amperes (charging circuit)
Battery:	12 volt, 32 ampere-hour

Tires:

	Front	Rear
Size	13 x 5.00 - 8	23 x 8.5 - 12
Pressure	12 psi	12 psi

Physical data:

Height:	104 cm	Wheel base :	116 cm
Length:	165 cm	Outside turning radius:	192 cm
Width:	92 cm	Dry mass :	270 kg

Liquid capacities:

Crankcase	:	1.4 liter
Transmission	:	1.9 liter
Fuel tank	:	11.4 liter

Chassis:

Zerk fittings	:	6
PTO brake adjustment (PTO engaged)	:	0.3 mm gap between brake pad and pulley

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[1]C-141 Owner's Manual, Wheel Horse, South Bend, Indiana.

EPT (E-141) Specifications[1]

Motor: 36 volt d-c permanent motor with built-in thermal overload circuit breaker

Batteries: 12 volt deep discharge (Golf Cart Type) rated at 90 amperes-hour-20 hour rate; or 155 minutes at 25 amperes.

Transmission:

Type : Mechanical, all gear
Number of forward speeds: 6
Number of reverse speeds: 2
Approximate ground speeds:

Gear	Low range	High range
First	0.7 km/hr	2.9 km/hr
Second	1.1 km/hr	4.7 km/hr
Third	2.0 km/hr	8.1 km/hr
Reverse	0.9 km/hr	3.8 km/hr

The electric motor is connected through a clutch to the transmission. There is no electrical speed control of the motor.

Electrical system:

Circuit voltage: Main--36 volt d-c, isolated ground
Lights--12 volt d-c, isolated ground

Power pack: Six 12 volt batteries series connected as two sets of three, with the sets wired in parallel

Power control: Brain in a box

Tires:

	Front	Rear
Size	16 x 6.5 - 8	23 x 8.5 - 12
Pressure	12-24 psi	12-15 psi

Physical data:

Height:	105 cm	Wheel base:	116 cm
Length:	175 cm	Outside turning radius:	221 cm
Width:	92 cm	Operational mass:	346 kg

Liquid capacities:

Transmission: 1.9 litre
Batteries: 5.7 litre/battery

Chassis:

Zerk fittings: 6
Front wheel end play: 0-0.04 cm

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[1] E-141 Owner's Manual, Wheel Horse, South Bend, Indiana.

APPENDIX C: CONVERSION FACTORS AND ENERGY COST

Conversion Factors

Area:	1 hectare (ha) = 10,000 square meters (m^2)
Length:	1 kilometer (km) = 1,000 meters (m)
Time:	1 hour (hr) = 60 minutes (min)
Volume:	1 milliliter (ml) = 1 cubic centimeter (cm^3) 1 litre (l) = 1,000 ml = 1,000 cm^3 1 U.S. gallon (gal) = 3,785.96 cm^3 = 3.78596 litres

Energy and Energy Cost

1 U.S. gal of gasoline = 1.25×10^5 Btu[1]

1 kw-hr = 3,414 Btu

Farm gasoline price = \$1.00/gal[2] (Iowa, November 1980)

Electricity price = 5.98¢/kw-hr (Ames, Iowa, November 1980)

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[1]See Johnson and Auth (1951).

[2]Gasoline for farm use is exempt from U.S. (4¢/gal) and Iowa (10¢/gal) fuel tax.